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Investigating the Effectiveness of Metaverse-Based Instruction on the Knowledge, Attitude, and Skills of Lower Secondary School Students in Experimental Sciences

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ABSTRACT

Emerging technologies such as the Metaverse hold considerable promise for transforming educational practices. This study examined the effectiveness of Metaverse-based instruction on the knowledge, attitude, and skills of lower secondary school students in the Science curriculum. A quasi-experimental pretest–posttest control group design was employed. The sample comprised 60 male students from one boys' school in Amol County, Iran, selected purposively during the 2025–2026 academic year. Two intact classes were randomly assigned to experimental ($n = 30$) and control ($n = 30$) conditions. The experimental group received 24 sessions of Metaverse-based instruction, while the control group followed conventional teaching. Four researcher-developed tests measured academic achievement, knowledge, attitude, and skill. Data were analyzed using ANCOVA and MANCOVA. After controlling for pretest scores, Metaverse-based instruction had a significant large effect on overall academic achievement, $F(1, 57) = 38.48$, $p < .001$, partial $\eta^2 = .40$. Significant improvements were also observed for knowledge (partial $\eta^2 = .13$), attitude (partial $\eta^2 = .28$), and skill (partial $\eta^2 = .54$). The multivariate test confirmed overall significance, Wilks' $\Lambda = .295$, $F(3, 53) = 42.14$, $p < .001$. These findings suggest Metaverse-based instruction can complement conventional teaching for enhancing science outcomes. However, given the single-school, all-male sample, generalization requires caution, and replication across diverse populations is recommended.

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1. Introduction

Science education is a foundation of students' scientific and critical-thinking development (Smith, 2020), yet traditional instructional methods are often criticized for limited interaction and low engagement among lower secondary students (Johnson & Lee, 2019). Emerging immersive technologies, including the Metaverse, have been proposed as a means of addressing these limitations by offering novel, interactive learning experiences (Radianti et al., 2020).

Conceptually, the Metaverse is described as a persistent, synchronized network of shared virtual environments in which individuals interact with one another and with digital objects through avatars (Hirsh et al., 2022; Chen & Lin, 2022). For the purposes of the present study, Metaverse-based instruction is operationally defined as instruction delivered through an avatar-mediated virtual environment that combines a persistent 3-D space, asynchronous interactive course content, and instructor-facilitated discussion forums — distinguishing it from a conventional, static Learning Management System (e.g., Moodle) or a synchronous video-conferencing platform (e.g., Zoom), which lack avatar embodiment and a persistent shared space (Luki, 2021; Dahan et al., 2022).

Theoretically, the potential of Metaverse-based instruction to support learning can be situated within constructivist and experiential learning perspectives. Social constructivist theory holds that learning is facilitated through active, socially situated engagement with a learning environment (Vygotsky, 1978), while experiential learning theory emphasizes that knowledge is constructed through direct, concrete experience and reflective observation (Kolb, 1984). Immersive, avatar-mediated environments such as the Metaverse are argued to operationalize both perspectives by allowing learners to manipulate and interact with three-dimensional representations of scientific phenomena that would otherwise be abstract, inaccessible, or hazardous to explore directly (Radianti et al., 2020; Dahan et al., 2022).

Experimental sciences in the lower secondary period have long faced challenges in achieving deep and lasting understanding among students, owing to the abstract nature of many concepts (such as atomic structure, chemical reactions, biological processes, and physical laws) (Kobilova et al., 2025; Amirbekova et al., 2023; Xie et al., 2023). Traditional teaching methods, which rely mainly on lecturing, two-dimensional images, and limited laboratory experiments, are often unable to provide learners with a tangible, interactive experience — a shortcoming that has become increasingly apparent in the post-pandemic era, as the use of digital technologies in education has accelerated markedly (Sripan & Jeerapattanatorn, 2025; Aziz et al., 2025; Sinha, 2023). In this context, Metaverse-based instruction has emerged as a novel, immersive approach that, by leveraging virtual reality, three-dimensional simulations, and real-time interaction, holds promise for transforming the science-learning experience (Youssef et al., 2024; AlMurtadha, 2025; Kim et al., 2023).

Within Iran, empirical research on Metaverse-based instruction in the experimental sciences curriculum at the lower secondary level remains limited (Ahmadi, 2023). Given the potential of this approach and the gap in the local literature, the present study investigated the effectiveness of Metaverse-based instruction on the academic achievement — and its knowledge, attitude, and skill components — of male ninth-grade students in Amol County. It is worth noting that claims regarding the Metaverse's broader contribution to systemic outcomes such as educational equity remain largely conceptual at this stage (Garcia, 2020) and are not directly tested by the present single-school design; such claims are therefore not advanced here.

The present study therefore seeks to answer the fundamental question: “What effect does Metaverse-based instruction have on the knowledge, attitude, and skill of lower secondary students in experimental sciences?” More specifically, it seeks to identify the role of instructional design factors and implementation conditions in this effect. By addressing this gap in the research literature, the study aims to provide the practical and scientific evidence

needed to develop and optimize Metaverse-based curricula for teaching experimental sciences.

2 .Literature Review

- A growing body of empirical research supports the potential of Metaverse-based instruction in science-related domains. Studies report improvements in knowledge acquisition and retention (Li, Wu, & Yu, 2022), in understanding of the human digestive system (Marini et al., 2022), and in creative thinking and problem-solving during collaborative science experiments (Ding et al., 2025). A 2026 systematic review of 37 studies proposing the VIRTAS framework similarly reported that virtual laboratories and Metaverse platforms enhance understanding of abstract scientific concepts and support collaborative problem-solving (Immersive experiences in virtual science labs, 2026), and Gündüz (2026) reported that Metaverse applications were perceived by lecturers and prospective teachers as improving learning retention and motivation. Related work outside science education — including nursing skills training (An, 2022), maker education (Huang, 2023), and augmented-reality-based interventions on scientific concepts, computational thinking, and visual thinking (Qishta, 2018; Jouda, 2018; Al-Dahsi et al., 2017; Ahmad, 2016) — has reported comparable gains, though findings are drawn from varied contexts, age groups, and technologies and should not be generalized uncritically to the Metaverse specifically.
- A substantial body of research in recent years (2023–2026) has examined the effect of immersive technologies on science learning. Numerous meta-analyses and systematic reviews have shown that virtual reality and Metaverse environments can have a significant positive effect on students' academic achievement, conceptual understanding, and motivation in STEM subjects (Diao & Su, 2025; Geng & Su, 2024; Dhanil & Mufit, 2024; Chen et al., 2026; Cromley et al., 2023). For instance, Al Muqbil (2024), in a study of secondary school students, found that the use of Metaverse technology led to a significant increase in academic achievement and motivation in science. Likewise, Zhong et al. (2026), in a meta-analysis of systematic evidence, acknowledged the positive effect of virtual reality on the cognitive domain (particularly knowledge and higher-order thinking skills), although results in the affective and motivational domains were less consistent. In addition, Kobilova et al. (2025) emphasized the role of virtual reality in enhancing scientific literacy in secondary education, framing it as aligned with sustainable development goals.
- Despite this positive evidence, the research literature also reveals notable contradictions and gaps. Some studies have shown that mere immersion in a virtual environment, without careful instructional design aligned with learning objectives, does not necessarily improve educational outcomes, and in some cases has had only limited or moderate effects on learning (Liang et al., 2023; Xiangming et al., 2024; Lin et al., 2024). Samsudin et al. (2026), in a recent study, explicitly stated that “immersion alone is not sufficient,” identifying instructional design quality as a key factor in the perceived effectiveness of, and intention to use, educational virtual reality. Furthermore, practical challenges — including high costs, limited access to adequate infrastructure, insufficient teacher readiness, and ethical and privacy concerns — have posed serious barriers to the adoption and expansion of the Metaverse in educational systems (Sripan & Jeerapattanatorn, 2025; González Torres et al., 2024; Roy et al., 2025; Sujatha et al., 2025; Akyürek et al., 2024).
- Research on attitude and skill in this domain is likewise marked by heterogeneity. With respect to attitude, some findings point to increased appeal and acceptance of learning through avatar-based interaction, gamification, and the sense of presence within the Metaverse (Avinç & Doğan, 2025; S Chanda et al., 2024; Jafari, 2023), while other studies emphasize the role of perceived usefulness, ease of use, self-efficacy, and social support in shaping positive attitudes, showing that psychological and social factors can strongly influence students' willingness to use this technology (Al Kfairy et al., 2025; Mohammad et al., 2026; Chua & Yu, 2024; Man et al., 2026; Baudier et al., 2025). Regarding skill, although there is

evidence of enhanced practical, problem-solving, and collaborative skills within immersive environments (Cho et al., 2024; Hsu et al., 2025; Kandemir & Akman, 2026), the extent of impact on procedural and laboratory skills in experimental sciences depends on the structure of the activities and the feedback provided (Žunić et al., 2025; Beck et al., 2024; Samsudin et al., 2026).

In light of the above review, despite the numerous studies examining the effect of the Metaverse on learning, important research gaps remain that justify the need for the present study. First, most existing studies have focused on specific domains of learning (either purely cognitive or purely affective), and few have simultaneously examined all three domains — knowledge, attitude, and skill — within a single context. Second, the target population of most studies has been university students or students at higher educational levels, with the lower secondary period — owing to its distinct developmental and educational characteristics — receiving comparatively little attention. Third, the role of moderating variables such as instructional design quality, user readiness, and implementation conditions has not been systematically examined in prior research, contributing to contradictory findings and difficulty in generalizing results (Diao & Su, 2025; Zhong et al., 2026; Samsudin et al., 2026; Parrales Bravo et al., 2026). Finally, despite the emphasis on the importance of teaching experimental sciences at the lower secondary level as a foundation for future choice of scientific fields of study, there is insufficient documented evidence regarding the integrated effectiveness of Metaverse-based instruction on all three components of knowledge, attitude, and skill at this level (Al Muqbil, 2024; Kobilova et al., 2025; Chen et al., 2026; Chong et al., 2026).

3. Method

The present study is applied in terms of purpose and quantitative in terms of data collection, employing a quasi-experimental design with a pretest–posttest control group. The statistical population comprised all male students enrolled in lower secondary schools in Amol City during the 2025–2026 academic year.

As random selection from the entire population was not feasible, one boys' lower-secondary school was purposively selected, and two intact classes within that school were randomly assigned (via a lottery) to the experimental and control conditions, with each class containing 30 students. To increase initial equivalence and reduce bias arising from the lack of random assignment of individuals, a pairwise matching procedure based on prior academic performance was employed prior to group assignment. To this end, the previous semester's grades in Experimental Sciences for all 60 students were extracted from the school's information system, and the students in each class were separately ranked in descending order based on these scores. Subsequently, the highest score from the first class was paired with the highest score from the second class, the second with the second, and so forth, resulting in the formation of 30 pairs (each consisting of one student from the first class and one from the second class) with very closely matched prior scores.

A coin toss then randomly designated one of the two classes as the experimental group and the other as the control group; consequently, each pair ultimately included one participant from the experimental group and one from the control group, and the mean prior scores of the two groups differed by a negligible margin (less than 0.1 points). To quantitatively confirm this equivalence, an independent-samples *t*-test was conducted on the pretest scores (administered after the matching procedure), and the absence of significant differences in academic achievement, knowledge, attitude, and skill (all with *p*-values greater than 0.25) confirmed the success of the matching method and established the desirable equivalence of the two groups prior to the intervention.

The Metaverse-based educational program was implemented for the experimental group over 24 sixty-minute sessions (two sessions per week for 12 weeks), while the control group received the same curricular content over the identical number and duration of sessions

through conventional, teacher-led instruction involving lectures, question-and-answer exchanges, and board-based problem-solving.

The Metaverse platform utilized in this study was a three-dimensional web-based virtual environment named "Hor Educational Metaverse," developed by the research institute's technical team using the Unity game engine and the WebXR library; it was hosted on a dedicated university server and accessible through modern browsers such as Chrome, Edge, and Firefox. This environment featured a 3D classroom space including a virtual board, interactive desks, and content display screens, and each student navigated the space using a personalized avatar, interacting with educational objects by clicking on them.

The content sequence for each session was designed in a step-by-step and compulsory order, such that subsequent stages were automatically activated only upon the completion of preceding ones. Communication tools within this platform included a text-based discussion forum (group chat) and an in-app messenger for posing questions to the teacher, and immediate visual and numerical feedback was provided to students following interactive activities such as simulated experiments. Students in the experimental group were required to have a personal computer or tablet with at least a Core i3 processor, an internet connection with a minimum bandwidth of 5 Mbps, an up-to-date browser, headphones and a microphone (for optional audio communication), as well as a mouse and keyboard; it should be noted that virtual reality (VR) headsets were not utilized, and all interactions were conducted through a two-dimensional screen using mouse controls.

The educational content was developed based on the eighth-grade Experimental Sciences textbook and organized into four main modules: the first module covered cellular biology and tissues (sessions 1 to 6), featuring topics such as cell structure with a virtual microscope, membrane and material transport with permeability simulations, cell division with interactive animations, and examinations of animal and plant tissues using 3D samples; the second module addressed basic chemistry and materials (sessions 7 to 12), encompassing atoms and elements with rotatable models, an interactive periodic table, chemical bonding with electron-sharing simulations, ionic and molecular compounds, acids and bases with a virtual laboratory, and the application of materials in daily life; the third module focused on physics (force and motion) (sessions 13 to 18), including the concept of force with push-and-pull simulations, Newton's laws with a motion simulator, friction, work and energy with interactive puzzles, simple machines, and power and efficiency; and the fourth module covered geology and the environment (sessions 19 to 24), addressing Earth's structure with 3D cross-sections, rock and mineral identification, erosion and sedimentation with rainfall simulations, energy resources, pollution and environmental protection, and finally a comprehensive review. Each session was structured so that upon entering the environment, students first watched a brief educational video or animation (5 minutes), then engaged in the main interactive activity (30 minutes), followed by discussion and exchange in the forum (15 minutes), and concluded with a 10-item quiz (10 minutes); the teacher, acting as a facilitator, continuously monitored each student's progress in real time through a management dashboard.

The data collection instruments comprised four researcher-developed tests designed to measure the dependent variables: academic achievement, knowledge, attitude, and skill. The knowledge test included 20 multiple-choice questions, each worth 1 point (total of 20 points), with components encompassing recall of concepts (5 questions), comprehension and interpretation (8 questions), and application of concepts in novel situations (7 questions); a sample item was "Which of the following options correctly describes the cell membrane? a) Fully permeable, b) Semi-permeable, c) Impermeable, d) Selectively permeable based on size," and scoring was conducted as +1 for a correct answer and 0 for an incorrect answer (with no negative marking). The attitude test comprised 15 items based on a five-point Likert scale (ranging from strongly disagree = 1 to strongly agree = 5), with components including attitude toward learning science (5 items), attitude toward the use of technology in education

(5 items), and self-efficacy in science subjects (5 items); scoring was performed by summing the total points (ranging from 15 to 75), and 5 negatively worded items were reverse-scored, with a sample item being "Can the use of virtual environments make learning science concepts more appealing to you?" The skill test consisted of 10 essay-type/practical questions requiring students to describe the steps of a simple experiment or problem-solving process, with each question worth 3 points (total of 30 points); its components included experimental design (3 questions), analysis of hypothetical data (4 questions), and interpretation of results (3 questions), and scoring was carried out according to a researcher-developed correction guide using specific criteria such as accuracy, logical sequence, and mention of safety precautions (each question scored from 0 to 3); a sample question was "Write the sequential steps for preparing a dilute solution from concentrated sulfuric acid and list the safety precautions."

The academic achievement test, as a composite variable, contained 45 questions drawn from the three aforementioned sections (20 knowledge questions, 15 attitude items, and 10 skill questions), with a total score calculated out of 125 and subsequently converted to percentages in the tables; its components corresponded to the three components above, and scoring was conducted by summing the scores of the three sections without additional weighting. All tests were administered in both pretest and posttest phases using parallel versions (identical in content and difficulty level).

To confirm the content validity of the instruments, a panel was formed comprising 10 faculty members from the Universities of Tehran and Mazandaran in the fields of educational sciences, psychology, and experimental sciences, as well as 15 experienced experimental sciences teachers from lower secondary schools. The experts were asked to rate each item based on three criteria—"relevance to the construct," "clarity and precision," and "appropriateness of difficulty level for eighth-grade students"—on a four-point scale (ranging from 1 = inappropriate to 4 = completely appropriate). Additionally, the Content Validity Ratio (CVR) for each item was calculated based on the experts' judgments regarding the "necessity" of the item. After collecting the evaluations, the Content Validity Index (CVI) was calculated using the method of expert agreement on ratings of 3 and 4, yielding a total CVI of 0.89 across all tests.

However, the minimum CVI, pertaining to one attitudinal item, was 0.76; based on the established criterion ($CVI \geq 0.78$ accepted, 0.70–0.78 required revision, and below 0.70 rejected), a decision was made to revise that item. Based on expert feedback, two items from the knowledge test were eliminated due to low CVR and conceptual overlap; three items from the attitude test with CVI values between 0.70 and 0.78 were rewritten and re-presented to the panel, and after re-approval, they remained in the final instrument; and one item from the skill test was thoroughly revised due to unclear instructions, with an example added to the student guide. Following these modifications, all instruments achieved a minimum CVI of 0.82 and a CVR greater than 0.56 (based on Lawshe's table) and were thus confirmed for final administration.

The reliability of the instruments was additionally estimated using Cronbach's alpha coefficient, which yielded values of 0.76 for knowledge, 0.78 for attitude, 0.83 for skill, and 0.71 for academic achievement.

Prior to conducting the main inferential analyses, the assumptions of parametric tests were examined using the Kolmogorov–Smirnov test to assess the normality of score distributions, Levene's test to verify the homogeneity of variances, and the test for homogeneity of regression slopes through the pretest $\times$ group interaction, all of which were confirmed. Finally, to compare the groups while controlling for pretest scores, univariate analysis of covariance (ANCOVA) was utilized for each dependent variable separately, and multivariate analysis of covariance (MANCOVA) was used for the combined set of variables. All statistical analyses were performed using SPSS version 26.

Table 1. Means and Standard Deviations for Academic Achievement and Its Components in the Experimental and Control Groups at Pretest and Posttest

Variable	Group	Pretest M	Pretest SD	Posttest M	Posttest SD
Academic Achievement	Experimental	22.47	5.67	49.17	6.21
	Control	22.53	6.95	40.07	4.99
Knowledge	Experimental	7.23	2.46	16.13	2.29
	Control	7.60	3.06	14.20	2.71
Attitude	Experimental	7.73	2.00	16.13	2.52
	Control	7.33	2.14	13.20	2.16
Skill	Experimental	8.20	2.40	17.10	1.94
	Control	8.33	2.50	12.67	2.23

Table 2. Independent-Samples t-Test for Baseline (Pretest) Equivalence Between Groups

Variable	t	df	Sig. (2-tailed)
Academic Achievement	-0.04	58	.968
Knowledge	-0.51	58	.611
Attitude	0.75	58	.457
Skill	-0.21	58	.834

4. Findings

Table 1 (above) presents descriptive statistics for academic achievement and its components.

Posttest means were higher for the experimental group than for the control group on all four variables, while pretest means were closely comparable between groups (Table 2), consistent with successful matching prior to the intervention.

Table 3. Kolmogorov-Smirnov Test for Normal Distribution of Paired Samples for Academic Achievement and Its Components

Variable	K-S Statistic	df	Sig.
Academic Achievement (Pretest)	0.087	60	0.720
Academic Achievement (Posttest)	0.120	60	0.327
Knowledge (Pretest)	0.150	60	0.123
Knowledge (Posttest)	0.142	60	0.163
Attitude (Pretest)	0.152	60	0.112
Attitude (Posttest)	0.100	60	0.549
Skill (Pretest)	0.135	60	0.202
Skill (Posttest)	0.123	60	0.299

Table 4. Levene's Test for Equality of Variances in Paired Samples for Academic Achievement and Its Components

Variable	F	df1	df2	Sig.
Academic Achievement (Pretest)	1.353	1	58	0.249
Academic Achievement (Posttest)	0.818	1	58	0.369
Knowledge (Pretest)	1.192	1	58	0.279
Knowledge (Posttest)	1.238	1	58	0.270
Attitude (Pretest)	0.052	1	58	0.821
Attitude (Posttest)	1.030	1	58	0.314
Skill (Pretest)	0.205	1	58	0.652
Skill (Posttest)	0.470	1	58	0.496

Table 5. Test of Homogeneity of Regression Slopes (Pretest $\times$ Group Interaction)

Dependent Variable	F	df1	df2	Sig.
Academic Achievement	1.54	1	56	.220
Knowledge	0.02	1	56	.892
Attitude	0.20	1	56	.660
Skill	0.23	1	56	.637

Table 6. Results of Univariate Analysis of Covariance (ANCOVA) for Academic Achievement

Variable	Sum of Squares	df	Mean Square	F	Sig.	Partial η^2
Academic Achievement (Pretest)	0.019	1	0.019	0.00	.981	0.000
Group	1242.166	1	1242.166	38.48	<.001	0.403
Error	1840.015	57	32.281			
Total	3082.199	59				

According to Table 6, after controlling for the pretest effect, the main effect of Metaverse-based instruction on academic achievement was statistically significant, $F(1, 57) = 38.48$, $p < .001$, partial $\eta^2 = .40$. Following Cohen's (1988) conventions for partial eta squared (.01 = small, .06 = medium, .14 = large), this corresponds to a large effect. The pretest covariate was not significantly related to posttest academic achievement, $F(1, 57) = 0.00$, $p = .981$, indicating that prior academic performance did not influence posttest outcomes independent of group membership. Adjusted posttest means were 49.17 for the experimental group and 40.07 for

the control group. These results support the first research hypothesis: Metaverse-based instruction was associated with a statistically significant, large improvement in students' academic achievement relative to conventional instruction.

To address the second research question, a Multivariate Analysis of Covariance (MANCOVA) was conducted on the knowledge, attitude, and skill components jointly, with the corresponding pretest scores entered as covariates. Table 7 presents the multivariate test statistics for the effect of group membership, and Table 8 presents the univariate follow-up results for each component.

Table 7. Multivariate Tests for the Effect of Group on Knowledge, Attitude, and Skill (Controlling for Pretest Scores)

Effect	Value	F	Hypothesis df	Error df	Sig.
Wilks' Lambda	0.295	42.14	3	53	<.001
Pillai's Trace	0.705	42.14	3	53	<.001
Hotelling's Trace	2.386	42.14	3	53	<.001
Roy's Largest Root	2.386	42.14	3	53	<.001

Table 8. Univariate Follow-Up Results (ANCOVA) for Academic Achievement Components

Dependent Variable	Source	Sum of Squares	df	Mean Square	F	Sig.	Partial η^2
Knowledge	Pretest	0.163	1	0.163	0.03	.874	0.000
	Group	55.411	1	55.411	8.67	.005	0.132
	Error	364.104	57	6.388			
Attitude	Pretest	1.786	1	1.786	0.32	.573	0.006
	Group	124.894	1	124.894	22.49	<.001	0.283
	Error	316.481	57	5.552			
Skill	Pretest	3.084	1	3.084	0.70	.406	0.012
	Group	296.262	1	296.262	67.47	<.001	0.542
	Error	250.283	57	4.391			

Table 9. Adjusted (Covariate-Controlled) Posttest Means by Group

Variable	Experimental Adjusted M	Control Adjusted M
Academic Achievement	49.17	40.07
Knowledge	16.13	14.20
Attitude	16.12	13.22
Skill	17.11	12.66

The univariate follow-up tests (Table 8) indicated that, after controlling for pretest scores, Metaverse-based instruction had a statistically significant effect on knowledge, $F(1, 57) = 8.67$, $p = .005$, partial $\eta^2 = .13$ (a medium effect); on attitude, $F(1, 57) = 22.49$, $p < .001$, partial $\eta^2 = .28$ (a medium-to-large effect); and on skill, $F(1, 57) = 67.47$, $p < .001$, partial $\eta^2 = .54$ (a large effect). None of the three pretest covariates was significantly related to its corresponding posttest score (all $p > .40$). These results, together with the significant multivariate test (Table 7), fully support the second research hypothesis: Metaverse-based instruction had a statistically significant, positive effect on the knowledge, attitude, and skill components of academic achievement.

5. Discussion

This study examined the effectiveness of Metaverse-based instruction on academic achievement — and its knowledge, attitude, and skill components — among male ninth-grade lower secondary students in experimental sciences. After controlling for pretest scores, students who received Metaverse-based instruction showed significantly higher knowledge scores than students who received conventional instruction, consistent with prior research (Immersive experiences in virtual science labs, 2026; Gündüz, 2026; Xie et al., 2025; Arslan & Görgülü Arı, 2025; Çetin & Türkmen, 2025; Lee et al., 2022; Marini et al., 2022; Huang, 2023; Girgis, 2017; Al-Dahsi et al., 2017). One plausible explanation, consistent with the constructivist and experiential learning perspectives outlined in the Introduction, is that the Metaverse environment supports the construction of knowledge by rendering abstract scientific concepts as concrete, visual, three-dimensional experiences; however, as no cognitive-load or memory measures were collected in this study, this explanation should be regarded as a hypothesis for future research rather than a demonstrated mechanism.

Students in the experimental group also reported significantly more positive attitudes toward the science course, consistent with Qishta (2018), Jouda (2018), Marini et al. (2022), and Ahmad (2016), and demonstrated significantly greater gains in practical skill, consistent with López-Belmonte et al. (2022) and Al-Dahsi et al. (2017). As with the knowledge findings, the specific mechanisms proposed to underlie these gains — such as increased engagement, opportunities for risk-free practice, or enhanced socialization (Liou, 2012) — were not directly measured in the present study and should likewise be treated as candidate explanations rather than confirmed findings.

This study has several limitations that should be considered when interpreting its findings. First, the sample was drawn from a single, all-male school in one city, which limits the generalizability of the findings to female students, other schools, and other regions; replication across multiple, mixed-gender schools is needed before broader claims can be made. Second, the relatively small sample size ($n = 60$) constrains the statistical power of the multivariate analyses and the precision of the effect-size estimates. Third, the intervention was relatively short (24 sessions), and longer-term or delayed-posttest designs would help clarify the durability of any observed effects. Fourth, as noted above, the mechanisms proposed to explain the intervention's effects were not directly assessed and require dedicated measurement in future studies.

6. Conclusion

This study has several limitations that should be considered when interpreting its findings. First, the sample was drawn from a single, all-male school in one city, which limits the generalizability of the findings to female students, other schools, and other regions; replication across multiple, mixed-gender schools is needed before broader claims can be made. Second, the relatively small sample size ($n = 60$) constrains the statistical power of the multivariate analyses and the precision of the effect-size estimates. Third, the intervention was relatively short (24 sessions), and longer-term or delayed-posttest designs would help clarify the durability of any observed effects. Fourth, as noted above, the mechanisms proposed to explain the intervention's effects were not directly assessed and require dedicated measurement in future studies.

In sum, within the boundaries of a single-school, male-only, quasi-experimental design, Metaverse-based instruction was associated with meaningful gains in academic achievement and its knowledge, attitude, and skill components relative to conventional instruction. These findings suggest that Metaverse-based instruction may be a promising complement to conventional teaching in experimental science education, warranting larger, multi-site, and longer-term studies — including direct measurement of the cognitive and motivational mechanisms proposed here — before broader claims about its role in science education are advanced.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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